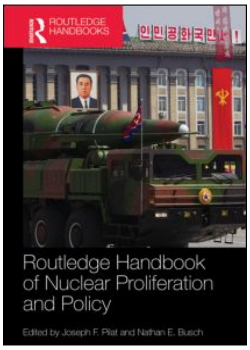

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Joseph F. Pilat, Nathan E. Busch

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Klaus Mayer, Alexander Glaser

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NUCLEAR FORENSICS

Klaus Mayer and Alexander Glaser

Whenever nuclear material is found out of regulatory control, questions on the origin of the material, on its intended use, and on hazards associated with the material need to be answered. Analytical and interpretational methodologies have been developed in order to exploit measurable material properties for gaining information on the history of the nuclear material. This area of research is referred to as nuclear forensic science or, in short, nuclear forensics. This chapter reviews the origins, types, and state-of-the-art of nuclear forensics; discusses the potential roles of nuclear forensics in supporting nuclear security; and examines what nuclear forensics can realistically achieve. It also charts a path forward, pointing at potential applications of nuclear forensic methodologies in other areas.

Background and definitions

Nuclear forensics has only recently emerged as a multidisciplinary area of research, combining methods of traditional forensics, radiochemistry, analytical chemistry, material science, isotope geochemistry, and nuclear physics. Nuclear forensics can "assist in the identification of the materials, as well as how, when, and where the materials were made, and their intended lawful use."[1] The capabilities of modern nuclear forensics are truly remarkable. Perhaps for this reason, nuclear forensics is often perceived as a scientific toolset that can easily and immediately answer every possible question an investigating authority might have about suspect nuclear material or about a related nuclear security event. In general, however, the process of nuclear forensic analysis is more complex. To appreciate this complexity, two fundamental distinctions have to be made: predetonation forensics versus postdetonation forensics and, most importantly, nuclear forensics versus attribution.

Predetonation versus postdetonation forensics

Postdetonation forensics was developed to detect and evaluate nuclear-weapon tests of adversaries during the Cold War period. In fact, the basic concepts underlying the method were already used by the United States to confirm the first Soviet test of a nuclear weapon, "First Lightning" or "Joe-1," in August 1949 using radiological methods on samples collected with airborne filters.[2] In contrast, predetonation nuclear forensics only gained significant attention since the early 1990s when interceptions of smuggled nuclear materials from the former Soviet Union were made in Europe, raising concerns about the possible existence of a black market for such material.

Analysis of the postdetonation debris of a nuclear device can be used to determine many predetonation characteristics. Specifically, when performed by experts from nuclear-weapon states, the analysis can reveal type, design, and level of sophistication of a weapon or device, which could also provide evidence about the origin of the material and the device. Technical challenges arise from the fact that the nuclear material was subject to extreme conditions and has subsequently been dispersed. In consequence, many of the macroscopic parameters describing nuclear material are lost. In this sense, postdetonation forensics relies on fewer signatures than predetonation forensics. In the hypothetical scenario of an explosion of a nuclear device, postdetonation forensics would generally involve a combination of unclassified and classified techniques and proceeds at a very different timescale than predetonation forensics.[3]

Nuclear forensics versus attribution

The boundaries between nuclear forensics and attribution are blurry. Strictly speaking, nuclear forensics consists exclusively in measurements made directly on the nuclear material or on other associated material. The interpretation of the measurement data allows describing the material (e.g., "the uranium in the sample contains 0.7 percent uranium-235"). Combining the description obtained from different parameters may then lead to nuclear forensic findings (e.g., "the impurity pattern in the uranium is consistent with natural uranium mined from sandstone deposits"). In contrast, an attribution process, in which the origin or route of intercepted nuclear material is reconstructed and perhaps even the group or individuals involved in an incident identified, combines the nuclear forensic findings with law enforcement and intelligence data. Hence, attribution requires interagency cooperation and an exchange of information between different communities. As highlighted below, attribution is a much more difficult and controversial process than the nuclear forensic analysis that it follows.

The technical basis and state of the art of nuclear forensic science

Fundamentally, nuclear forensic analysis seeks to determine parameters that describe physical, chemical, elemental, and isotopic properties of nuclear or other radioactive material of unknown origin. Predetonation nuclear forensics has significantly matured since its inception in the early 1990s and, today, a range of methods and analytical techniques are applied for measuring an increasing number of parameters that have been identified as being characteristic of the material.[4] As nuclear material may appear in quite a variety of chemical and physical forms throughout the nuclear fuel cycle, significant research and development efforts are required to identify useful signatures. Such development work in the laboratory, though being tedious and consuming time and resources, will result in methods and protocols that can be applied to seized material and provide useful clues. These methods include gamma spectrometry, alpha spectrometry, mass spectrometry, titration, chromatography, scanning electron microscopy, X-ray diffraction analysis, infrared spectroscopy, and Raman spectroscopy. The parameters to be measured may comprise the isotopic composition of the nuclear material, chemical form (e.g., oxide or metal), molecular structure, chemical impurities, isotopic composition of trace elements, physical form, and morphology. The development of an analytical plan, which prioritizes the parameters to be measured and the selection of the most suitable analytical methods, is the responsibility of the nuclear forensic laboratory undertaking the analysis. Such an analytical plan is established based on initial clues on the material, on circumstantial information, and on the insights the investigation authority wants to gain. Ultimately, the measured parameters form the basis of nuclear forensic findings.

Individual parameters or a combination of several parameters may be characteristic for the material and are referred to as "signatures." Two general types can be distinguished. Signatures that can be interpreted without additional information are called "predictive signatures." For example, the concentration of specific decay products in a sample determines the age of the material, i.e., the time that has elapsed since production or the last time material was purified. In contrast to that, "comparative signatures" require external data to understand the history of an unknown nuclear material. Comparative signatures are analogues to human fingerprints that have to be matched against a person or database, i.e., without a reference, they do not provide much information. In the case of nuclear forensics, the impurity pattern in natural uranium is an example of such a signature, as the comparison against literature values or databases enables matching a sample against a specific type of geological environment (uranium ore). Ideally, the original production facility and perhaps also the material's pathway until control was lost can be established with some or even high confidence.

Although material parameters such as the isotopic composition or chemical impurities can be measured with high precision and accuracy, the conclusions about the material history are often associated with significant uncertainties and do not always allow an unambiguous source attribution. The challenges associated with the confidence in conclusions arise from several factors, which are summarized below.

Analytical techniques

Confidence in the measurement results is generally achieved by using established and validated methods, by applying strict quality control, and by governing the entire process through a quality assurance program. The analytical techniques typically used in nuclear forensic investigations are well established and have served also for other applications. With the concept of "International Target Values," the IAEA defined uncertainty components that are considered to be reasonably and realistically achievable in routine measurements of nuclear material for safeguards purposes. The latest issue was published by the IAEA in 2010.[5] The uncertainty values listed in this document may serve as guidance also for measurements performed in the context of nuclear forensic investigations. The specific questions that may arise during a nuclear forensic analysis may, however, lead to the need for applying the technique in a way that is not covered by the method's initial validation. In other words, nuclear security incidents require a rapid and effective response, especially in the postdetonation scenario, and may trigger the necessity for employing methods that are not fully validated due to exigent circumstances of the incident.

Qualified experts

To carry out a nuclear forensic analysis, trained analysts with specific skills and experience in working with nuclear material are required. Moreover, subject matter experts need to be involved in interpreting the data and establishing the nuclear forensic findings. Throughout the entire nuclear forensic investigation (i.e., from sample taking to the data interpretation) the involvement of appropriately qualified and experienced experts is key to credible and defensible conclusions. Maintaining the "nuclear workforce" (e.g., through educational programs) and transferring tacit knowledge from one generation to the next (e.g., through vocational training of young professionals) are essential for sustaining nuclear forensic expertise.

Interpretational techniques

Interpretational techniques may be based on different approaches. Comparative evaluation for identifying the origin of unknown nuclear material can be performed using the exclusion principle, i.e., step-by-step reduction of the number of candidate facilities for the origin of an unknown nuclear material using an iterative process, which serves at the same time as analytical guidance.[6] Statistical methodologies have been adapted, which allow drawing conclusions from similarities between an unknown sample and a group of known materials based on multiple forensic parameters.[7] Simple one-to-one matching of unknown against known (as performed in fingerprint comparisons or in forensic DNA analysis) is rather unusual in the area of nuclear forensics.

Comparison data

Characterizing and archiving the parameters of material of known history is essential for understanding comparative signatures. Establishing comprehensive and systematic compilations of such data is still in its early stages. However, an understanding of relevant parameters has been developed based on the most characteristic signatures that have been identified.

Evidence management

Strict rules may have to be followed when the samples are linked to a criminal act, and the nuclear forensic findings are expected to support the prosecution. Close coordination between law enforcement and nuclear forensic investigators needs to assure compliance with procedural and legal requirements for entering nuclear forensic derived conclusions in a court of law.

Nuclear forensic investigations were conducted in a number of incidents and proved to provide useful information on the history of the seized material. This information either provided investigative leads or was directly used by the competent authority in the processing of the incident. The insights provided by (predetonation) nuclear forensic investigations in real incidents of illicit trafficking are important.

The emergence of illicit trafficking

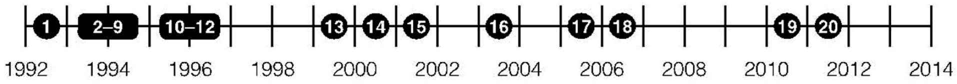
Although there is evidence for earlier cases of illicit trafficking of nuclear material,[8] the issue emerged as a more persistent phenomenon in the early 1990s, shortly after the dissolution of the Soviet Union. The investigations of these early cases of nuclear smuggling often involved the analysis of the seized nuclear material. In many cases, the material could be traced back to an application and to a country of origin. Although the methodologies for nuclear forensic analysis as we know them today were still in their infancy, the conclusions often appeared simple and straightforward. As the phenomenon of illicit trafficking persisted, nuclear forensics developed from an *ad-hoc* application of material characterization techniques to a full scientific discipline aiming at understanding correlations between measureable parameters and the process history of the material.

Incidents of illicit trafficking are collected in the IAEA's Incident and Trafficking Database (ITDB), which was established in 1995. As of the end of 2013, the database included 2,477 incidents. Only officially confirmed incidents are included in the database, however. In the order of fifteen incidents per year involve nuclear material. Most of these seizures involve gram quantities of material, and only in a few cases, kilogram amounts of low-enriched, natural, or depleted uranium were seized. The IAEA stopped reporting individual events in 2007. More recent incidents are taken from other sources, but have been publicly reported and confirmed.[9]

Overall, in about sixty cases, the effort of conducting a comprehensive nuclear forensic investigation was undertaken. While in the 1990s most of the seizures could be linked to intentional movement of nuclear material across borders and classified as "nuclear smuggling," at present most of the cases refer to contaminated scrap metal. Moreover, we observe a change on geographical focus of the phenomenon. During the first decade of illicit trafficking, most of the incidents were reported from central European states, while more recent trafficking cases were mainly discovered in southeastern European countries, i.e., the Black Sea region. Since the beginning of the 1990s, only a relatively small number of incidents involving highly enriched uranium or plutonium have been reported (see Figure 18.1). Two illustrative cases are discussed below.

1994 Munich plutonium

In August 1994, a person arriving at Munich Airport on a Lufthansa flight from Moscow was arrested based on a tip-off from intelligence. In his suitcase, he carried nuclear material, which was later identified as a mixture of 363 grams of plutonium and 122 grams of uranium. Apart from that, 210 grams of enriched lithium metal (89.4 percent Li-6) were discovered in his luggage. The analysis of the material revealed that the plutonium was low burnup (87 percent Pu-239), hence close to weapon-grade material. Microscopic investigations revealed different morphologies of the plutonium particles, indicating different production processes. A comparative evaluation against reference samples from a German MOX fuel fabrication plant clearly showed a much finer grain size distribution for the seized material, indicating a different production process. Age-dating of the plutonium (both on the bulk material and on individual particles) suggested a production date for the material of the end of 1979 with an uncertainty of about a half year. The isotopic composition of the plutonium proved to be consistent with plutonium produced in Russian RBMK reactors. The belief that the material was of Russian



1	1992	Podolsk, Russia	HEU, 1500 g
2	1993	Vilnius, Lithuania	HEU (50%), 100 g
3	1993	Andreeva, Russia	HEU (36%), 1800 g
4	1993	Murmansk, Russia	HEU (20%), 4500 g
5	1994	St. Petersburg, Russia	HEU (90%), 2970 g
6	1994	Tengen, Germany	Pu (99%), 6.2 g
7	1994	Landshut, Germany	HEU (88%), 0.8 g
8	1994	Munich, Germany	Pu (87%), 400 g
9	1994	Prague, Czech Republic	HEU (88%), 2730 g
10	1995	Prague, Czech Republic	HEU (88%), 0.4 g
11	1995	Moscow, Russia	HEU (20%), 1700 g
12	1995	Ceske B., Czech Republic	HEU (88%), 17 g
13	1999	Rousse, Bulgaria	HEU (72%), 10 g
14	2000	Batumi, Georgia	HEU (30%), 920 g
15	2001	Paris, France	HEU (72%), 2.5 g
16	2003	Georgia/Armenia, Border	HEU, 170 g
17	2005	New Jersey, USA	HEU, 3.3 g
18	2006	Tbilisi, Georgia	HEU, 79.5 g
19	2010	Georgia	HEU (89%), 18 g
20	2011	Moldova	HEU

Figure 18.1 Incidents involving HEU and plutonium confirmed in the IAEA Incident and Trafficking Database (ITDB), 1993–2007

origin was reinforced by findings that clearly excluded western-type light-water reactors as the origin of the plutonium. Russian experts later performed their own analysis of the intercepted material, but the results were never published. Overall, despite a remarkably detailed and successful forensic analysis, the background of the case was complex, involving actors in Germany, Russia, and Spain, and was never fully resolved. The controversial role of the German foreign intelligence service (the Bundesnachrichtendienst, or BND) in the incident became the center of a two-year government investigation.[10]

1999 Bulgarian HEU

In May 1999, a person traveling by car and attempting to cross the Turkish-Bulgarian border was found to be carrying 10 grams of HEU (72 percent U-235) in a lead container concealed in the trunk of the car. The material had an unusually high U-236 content of 13 percent, and a nine-month forensic analysis found that the material was reprocessed uranium from high-burn-up fuel and originally had a U-235 content of 90 percent. The investigation was "the most thorough and far-reaching analysis of illicit nuclear material ever conducted."[11] Nonetheless, the attribution of the Bulgarian HEU remained incomplete. "Despite the comprehensive forensic investigation and wealth of data, neither the original source of the HEU nor the point at which legitimate control was lost has yet been unambiguously identified."[12]

These two prominent examples illustrate how difficult a comprehensive reconstruction of a case (including identification of the masterminds behind it) can be, even if the forensic analysis is considered successful. Over the years, the expectations on the reliability of nuclear forensic investigations and on the comprehensiveness of conclusions have only grown. While these expectations are often unrealistic, a thorough examination of intercepted material always results in useful hints on the history of the material and provides investigative leads.

Data interpretation in nuclear forensic investigations relies on the ability to establish a linkage between measurable parameters (signatures) and processes to which the material was exposed. To this end, the availability of reference information (on material of known process history) plays an important role. Compilations of such reference information – or data bases – and the accessibility thereof, however, are facing challenges due to sensitivities of the data.

While nuclear forensic science continues to be developed and further perfected, we also have to realize that the threat has evolved. In the early 1990s, the main concern focused on the proliferation risks associated with nuclear material that had been removed from regulatory control. In the early 2000s, in particular following the events of 9/11, the threat of nuclear terrorism added another dimension to the efforts spent in measures of prevention and preparedness. In parallel, the expectations related to the role of nuclear forensics evolved as well with a view on the support it could provide to law enforcement by providing investigative clues and through the deterrent character associated with the public messages on its capabilities.

What can be the role of nuclear forensics today?

The capabilities of modern nuclear forensics in a variety of contexts are remarkable. While postdetonation forensics were routinely applied during the times of atmospheric testing, and predetonation forensics attracted much attention following the end of the Cold War, this still leaves the questions of what the key roles of nuclear forensics can or should be today and how priorities for future research and development should be set. The different dimensions of these questions are explored below.

Nuclear forensics for national and international security

Shortly after the 9/11 attacks, concerns about the possibility of radiological and nuclear terrorism began to move to the center of the security debate – especially in the United States.[13] Most alarming in this context was and still is the possibility – even if considered remote – that a terrorist organization could set off a nuclear device in a metropolitan area. Many consider such a scenario credible given the availability of highly enriched uranium (HEU) in significant quantities at dozens of civilian sites,[14] often with poor security,[15] and the interest of some groups in carrying out such an attack.[16] The use of HEU in an improvised nuclear device based on the gun-type method is not considered a major technical challenge.

The possibility of state-sponsored nuclear terrorism later also became a growing concern. This was partly a consequence of the exposure of the A.Q. Khan network, which had connections to Libya, North Korea, and Iran.[17]

Combined, these new concerns became a focal point of US domestic and foreign policy. In response, in November 2002, the US Department of Homeland Security was created. It would consolidate a number of agencies and later also establish the Domestic Nuclear Detection Office (DNDO), which is now in charge of a "managed and coordinated response to radiological and nuclear threats, as well as integration of federal nuclear forensics programs."[18] In October 2006, the National Technical Nuclear Forensics Center (NTNFC) was established within DNDO to "ensure a ready, robust, and enduring nuclear forensics capability, to advance capabilities to conduct forensics on nuclear and other radioactive materials."[19]

A number of security initiatives were also launched on the multilateral or international level. In 2003, the United States, together with a number of partner countries, launched the Proliferation Security Initiative (PSI), mainly focused on interdiction of shipments related to weapons of mass destruction.[20] This initiative was backed up in April 2004 by UN Security Resolution 1540, which imposes binding obligations on all states to adopt legislation to prevent, inter alia, the proliferation of nuclear weapons and, specifically, the illicit trafficking of equipment and materials.[21] Related to these latter efforts, the US government launched the "Container Security Initiative" and the "Megaports Initiative" to enhance radiation detection capabilities for nuclear and radioactive materials in containerized cargo in major ports worldwide (now part of the "Second Line of Defense Program"). Since 2004, the United States has significantly ramped up the efforts to clean out civilian highly enriched uranium worldwide, consolidated under the Global Threat Reduction Initiative (GTRI).[22] Finally, at the broadest level, the Global Initiative to Combat Nuclear Terrorism (GICNT), initiated in 2006, became a partnership of eighty-five countries and four international organizations aimed at strengthening "global capacity to prevent, detect, and respond to nuclear terrorism by conducting multilateral activities that strengthen the plans, policies, procedures, and interoperability of partner nations."[23]

Overall, since the events of 9/11, there have been unprecedented US domestic and international efforts to prevent the theft and curb the trafficking of radiological and nuclear materials.

Ultimately, nuclear forensics play a central role for most of these efforts, because it would be the critical tool to enable attribution were the preparations for a terrorist attack discovered or such an attack to occur and remain unclaimed.

Recognizing this importance, especially in the United States, a parallel debate about the status of nuclear forensics began. It was triggered by concerns that US capabilities are inadequate or eroding. An influential report by the American Association for the Advancement of Science together with the American Physical Society in 2008,[24] and a later report by the

National Academies (2010),[25] examined the status of US nuclear forensic capabilities and developed recommendations to maintain a robust program.[26] Both reports emphasized, inter alia, the importance of international cooperation, including database development and the need for a larger forensic workforce, and recommended the accelerated development and deployment of state-of-the-art forensic techniques.

Attribution became a central theme in this discussion with a particular focus on the deterrent effect that would come with a robust attribution capability. The rationale behind this argument is that, unlike states, terrorist groups cannot be deterred to carry out an attack. Instead, credible attribution would need to identify the state sponsor, who provided fissile material for an "indirect" attack. This thinking is perhaps best summarized by Graham Allison in 2006 about then-North Korean leader, Kim Jong-il:

> Kim must be convinced that American nuclear forensics will be able to identify the molecular fingerprint of nuclear material from his Yongbyon reactor. He must feel in his gut the threat that if a nuclear weapon of North Korean origin explodes on American soil or that of a US ally, the United States will retaliate precisely as if North Korea had attacked the United States with a nuclear-armed missile: with an overwhelming response that guarantees this will never happen again.[27]

Some analysts continue to argue that a robust forensic and attribution capability can provide strong deterrence against illicit use of nuclear weapon materials.[28] The argument is based on the correct premise that production of fissile material is beyond the capabilities of nonstate groups. If such a group were therefore to acquire fissile material for a terrorist attack, it would ultimately be the responsibility of the country that had lost the control over the material.

There are several problems with the concept of deterrence through attribution capability, however. First, a thorough forensic analysis would likely require several months and be overtaken by events – especially following a hypothetical postdetonation situation. Second, if a state would indeed "plan" to use nuclear material for an unattributed attack or plan to transfer this material to a nonstate actor with explicit or tacit approval for use in a terrorist attack, it would make every effort to use material that is not in a forensic database. Similarly, those countries that are actively supporting the establishment and maintenance of nuclear forensic databases today are also the least likely to later provide nuclear material to third parties for illicit purposes. Finally, even if the origin of a material could be identified with high confidence, how would intent versus negligence be established? After all, given the sheer quantities of fissile material in the US and Russian stockpiles (e.g., more than 90 percent of the global HEU stockpile),[29] it is also quite possible that orphan nuclear material could ultimately be traced back to one of those sources. In brief: What kind of forensic evidence "justifies" what kind of response? However, even an incomplete attribution capability can be of significant value, of course, because it might help *exclude* certain origins for some recovered material and therefore help reduce uncertainty in an unfolding crisis.

In the United States, the establishment of strong attribution capabilities has been formalized with the Nuclear Forensics and Attribution Act, enacted in February 2010. The act asks the president to "pursue bilateral and multilateral international agreements to establish an international framework for determining the source of any confiscated nuclear or radiological material or weapon, as well as the source of any detonated weapon and the nuclear or radiological material used in such a weapon" and to "develop expedited protocols for the data exchange and dissemination of sensitive information needed to publicly identify the source of a nuclear detonation."[30]

A variation on the deterrence-through-attribution argument – one that is perhaps more practical – is the idea of leveraging strong attribution capabilities to encourage states to pursue and enforce the highest security standards for their nuclear materials. In particular, analysts have argued for a "global campaign leading to unambiguous physical protection standards." Pre-detonation nuclear forensics and attribution would be the critical tool to support and enforce such an effort.[31] These ideas have been an important theme of the Nuclear Security Summits held in 2010, 2012, and 2014.

Nuclear forensic methodologies for IAEA safeguards

Nuclear forensic science was first developed in a nuclear security context. The analytical methodologies that were developed and established, however, are being transferred to modern IAEA safeguards.

Nuclear forensic methods were first introduced as an ad-hoc tool used by the IAEA in May 1992 during its first inspections in North Korea. Shortly after North Korea's safeguards agreement with the agency entered into force, and following North Korea's submission of its "initial report" (as required by INFCIRC/153),[32] a high-level IAEA delegation visited the Yongbyon nuclear site, which had raised suspicions ever since a 5-MWe graphite reactor and a reprocessing plant were under construction there. During this visit, IAEA staff took swipe samples in the radiochemical facility, which would later reveal substantive inconsistencies in North Korea's initial report. For example, forensics analysis of more than 800 plutonium particles picked up in glove boxes indicated different isotopic signatures and different production dates (1989, 1990, and 1991), whereas North Korea only declared a single reprocessing campaign carried out in 1990.[33]

With the implementation of the Additional Protocol (INFCIRC/540) in the late 1990s, environmental swipe sampling techniques have become a routine safeguards tool.[34] The technique can be used, for example, to support conclusions about the absence of HEU production in a declared enrichment facility. Similarly, for bulk sample analysis, the measurement of impurities in nuclear materials, for example in uranium samples, allows safeguards authorities to verify the consistency of information. In combination with pattern recognition techniques, the analysis of chemical impurities enables one to check whether a sample does indeed originate from a particular facility or process stream. These safeguards applications are being supported by comprehensive investigations on the stability of impurity patterns throughout a chemical process as experienced, for example, from uranium mining to conversion. High-accuracy measurements of the isotopic composition of natural uranium samples have also proven to help distinguish between batches of different geographic origin.[35] Overall, modern nuclear forensic techniques have become an indispensable tool for IAEA safeguards.

Nuclear forensics for arms control and verification

Following the end of the Cold War, the United States and Russia agreed on a number of bilateral agreements related to the elimination, management, or disposition of excess fissile materials. Most importantly, this included the 1993 HEU blend-down agreement, under which Russia eliminated 500 metric tons of weapon-grade highly enriched uranium between 1993 and 2013, and the 2000 plutonium management and disposition agreement (PMDA), under which both sides have agreed to dispose of 34 metric tons of weapons plutonium. Both agreements have provisions based on isotopic measurements to ensure that weapon-grade material is being processed.[36] Besides these bilateral precedents, verification of nuclear arms control agreements has so far not systematically used nuclear forensic or other measurement techniques on nuclear materials. Future arms control treaties, however, could envision a more central role for nuclear forensics to support treaty verification. The most important examples and opportunities are briefly discussed below.

Comprehensive Test Ban Treaty (CTBT)

Verification of the CTBT would be based on an extensive International Monitoring System (IMS) using a variety of sensors to detect nuclear explosions in the atmosphere, underwater, and underground. In most circumstances, e.g., in the case of an underground explosion, attribution of a detected nuclear explosion would not be difficult or controversial. In some other scenarios, however, attribution could be challenging, especially of course if the country conducting the test sought to evade detection or attribution by carrying out the test in a remote location or in international waters. The most striking historic example remains the "mysterious flash" in the South Atlantic, which was detected by a dedicated satellite in September 1979 ("Vela Event 747"). No country claimed credit and no country was unambiguously identified as having conducted the test, but the most plausible explanation for the event remains a clandestine Israeli weapons test.[37] In the aftermath of the event, efforts were made to collect airborne radioactive debris in the region, but direct forensic evidence remained elusive.

Today, the CTBT monitoring system, which includes eighty state-of-the-art radionuclide stations worldwide, would have a much better chance of picking up unique signatures that would help characterize such an event. More importantly, postdetonation forensics could then be used to solve the "inverse problem" and determine features of the exploded device. Combined, these findings could provide critical evidence in attributing a clandestine nuclear-weapon test and confirming a possible violation of the CTBT.

Fissile Material Cutoff Treaty (FMCT)

The idea of banning the production of fissile materials for weapons purposes goes back to the late 1950s, but only with the end of the Cold War did NPT weapon states begin to seriously consider an FMCT. Efforts to start negotiations on an FMCT have been underway at the Conference on Disarmament since 1996. The overall scope of a possible FMCT has been a contested issue, in particular, if and how existing stocks of fissile materials in weapon states would be captured under such a treaty. Similarly, details of the verification regime would have to be agreed upon during the negotiations, even though many tools and approaches of the IAEA safeguards system could be directly applied. In fact, the NPT already constitutes a cutoff treaty for nonweapon states. Yet, an FMCT would also pose some new verification challenges, and nuclear forensics could help resolve some of them. By definition, nuclear-weapon states have military stocks of fissile materials and, while new production of fissile material for weapon purposes would be banned under the treaty, former military production facilities may continue to operate after conversion to civilian use. Situations may then arise, where the production date of a material sample needs to be determined to help confirm treaty compliance.

Enrichment plants are particularly relevant because historic HEU production can be expected to be reflected in particles collected in swipe samples, which are now used on a routine basis in safeguarded plants. The age of a macroscopic (microgram) uranium sample can easily be determined with nuclear forensic methods based on trace quantities of specific decay products in the sample.[38] Most importantly, the trace isotope uranium-234 decays to thorium-230 with a half-life of 246,000 years. A forensic analysis can then determine the fractional thorium-230 content in uranium to estimate the production date, i.e., the time elapsed since the last chemical separation of the parent nuclide from its daughter nuclide. The challenge arises in the case of microscopic (micron-sized) particles containing only few picograms of uranium. Such particles are typical for swipe samples taken at nuclear facilities. Here, the number of thorium-230 atoms could be as low as 100,000 in a particle that is 20–40 years old. Advanced ultra-sensitive mass-spectrometry begins to achieve such extreme, and previously unimaginable, detection goals.[39] The fact that many weapon states stopped production of weapons materials decades ago works in favor of the method. The potential contributions of nuclear forensics for FMCT verification can therefore only increase over time.

Verified fissile material declarations for nuclear disarmament

This is the most unconventional, but potentially also the most important application of nuclear forensics in the area of arms control verification. Existing nuclear arms control agreements between the United States and Russia place limits on the number of *deployed* strategic nuclear weapons. Verification of these agreements, such as New START, take advantage of the fact that deployed weapons are associated with unique and easily accountable delivery platforms, i.e., missile silos, submarines, and strategic bombers, to which agreed numbers of warheads are attributed. The next round of nuclear arms control agreements, however, may place limits on the *total* number of nuclear weapons and warheads in the arsenals. Such agreements would require fundamentally new verification approaches.[40]

One particular unprecedented challenge will be to gain confidence in the *completeness* of a declaration made by a country about the total size of its warhead stockpile, i.e., to ensure that an undeclared (secret) arsenal of nuclear weapons does not exist outside the verification regime. This is sometimes referred to as the "baseline problem."

One strategy – perhaps the only strategy – to systematically address this challenge is to focus on fissile material production and use instead. Weapon states have generally re-manufactured nuclear warheads on a regular basis. As a consequence, every kilogram of fissile material may have been in a number of warhead components since it was originally produced. In other words, most warheads produced since the beginning of the nuclear era no longer exist, and it may be extremely difficult or impossible to independently verify *ex post facto* that they have indeed been dismantled. If, however, confidence in the completeness of a state's fissile material declaration could be gained, then this could indirectly also serve to confirm the completeness of a nuclear warhead declaration. Confidence in the completeness would increase over time as the nuclear arsenals are drawn down and fissile materials are recovered from warheads, declared excess, and placed under international monitoring.

The United States and the United Kingdom have already made declarations about their respective inventories of military plutonium and highly enriched uranium. The US declarations are particularly valuable: they provide substantial detail on acquisition and use, include production data by year and site, and also list basic isotopic information of different material stocks. Confidence in the completeness of a fissile material declaration could be gained with a process dubbed "nuclear archaeology," which essentially relies on nuclear forensic analysis. The fundamental idea is to collect forensic evidence at former production facilities that can help establish total fissile material production at the site. The best-established example of nuclear archaeology was first proposed in the early 1990s and relies on measurements of the buildup of transmutation products in the graphite of graphite-moderated plutonium production reactors.[41] This so-called Graphite Isotope-Ratio Method (GIRM) estimates the cumulative neutron flow through the graphite and thereby the cumulative plutonium production in the reactor.

Equivalent methods might be used with other types of reactors, especially with heavy-water-moderated reactors that have been used for military plutonium production,[42] and possibly also for uranium enrichment plants.[43] In the best case, uncertainties in the lifetime production estimate of a particular facility can be in the order of a few percent,[44] but this would still translate into large absolute amounts of fissile material in terms of weapon-equivalents, especially in the cases of the United States and Russia. Combined with some other forensic evidence, however, estimates can be expected to be significantly more accurate. Overall, nuclear archaeology benefits from the fact that large amounts of source material and several production steps in different types of facilities are required for every kilogram of fissile material made.[45]

So far, the potential of nuclear archaeology to reconstruct fissile material production histories has only been demonstrated in a number of exercises; in one case, however, the method could have helped resolve the North Korean nuclear crisis. As part of the Six Party Talks,[46] in June 2008, North Korea reported its plutonium stockpile and use. In the same month, the United States submitted a discussion paper proposing elements of the verification activities to confirm the completeness of North Korea's declaration. The paper proposed to "conduct forensic measurements of nuclear materials and equipment" and, in the case of the Yongbyon graphite-moderated reactor, to "collect, and remove from the Party physical samples of the graphite moderator after the core has been de-fueled."[47] In October 2008, North Korea agreed on a number of verification measures, including access to all nuclear sites, and the use of scientific procedures to confirm the correctness and completeness of the declaration – but the process fell apart before the stage of sampling for nuclear forensics was reached. Given that North Korea had only produced in the order of 30–50 kilograms of plutonium by 2008, a nuclear archaeological analysis with a 5 percent error would have been equivalent to a maximum uncertainty of 2.5 kilograms of plutonium; in other words, at the time, the forensic analysis could have effectively excluded the existence of an undeclared nuclear device in the North Korean nuclear arsenal.

Overall, nuclear forensics, combined with other forensic evidence (including original production records), could therefore provide the critical tools to verify the completeness of fissile material declarations. Analysts have also emphasized that the sooner a nuclear archaeological analysis can be undertaken, the smaller the uncertainties in the estimate of lifetime fissile material production for a given facility.[48]

In principle, nuclear forensic techniques used for nuclear archaeology would not directly involve the fissile stocks themselves, which helps avoid security concerns that nuclear-weapon states may otherwise have. It should be noted, however, that direct measurements on fissile materials could considerably enhance confidence in nuclear archaeology, but would require countries to declassify isotopic information. Revealing such properties to international inspectors would be considered unacceptable by some nuclear-weapon states today. Once countries are willing to declare their fissile-material stockpiles, however, the security impact of the additional information made available during the verification of those declarations would be relatively minor.

Where do we stand? Where do we go from here?

Increasing the confidence in nuclear forensic conclusions and broadening the range of applications of nuclear forensic methodologies relies on accurate and sensitive analytical methods and on the availability of reference data for (comparative) evaluation of the observations. As distinguished from "predictive signatures," which do not require comparison data, and "comparative signatures," most of the signatures used in nuclear forensic investigations are of comparative nature, which necessitate the availability of empirically established data on material of known process history. The latter signatures provide more robust conclusions and allow establishing the history of unknown material with higher confidence. To some extent, reference information can be obtained from open source information and from the scientific literature. Yet, in order to enable drawing defensible conclusions, the availability of reference information (e.g., through appropriate databases) is essential. Such compilations could be realized through nuclear forensic databases or sample archives, sometimes referred to as "nuclear forensic libraries."

Ideally, one should strive for a comprehensive international database, in which data on all the signatures of all nuclear material is stored. In case of a nuclear security incident, the relevant reference data enabling a rapid and unambiguous identification of unknown material would be readily available. Such an approach, however, has proven too difficult to implement, and, in hindsight, unrealistic because data on nuclear material is associated with sensitivities, which can be due to commercial or national security issues. These sensitivities appear prohibitive for establishing an international database. In consequence, efforts were made to support the development of national nuclear forensics libraries, allowing states to keep control of the data and ensure the protection of sensitive information. The shortcomings of this approach are obviously the distribution of data (in national databases) and the delay involved when asking for queries in the databases of other states. Such a distributed approach obviously calls for an international directory, i.e., an overview of where national nuclear forensic libraries are available and of how queries can be requested.

The Nuclear Security Summits in 2010 and 2012 emphasized the importance of nuclear forensics and developed a number of related recommendations. Specifically, the Work Plan of 2010 listed a number of political commitments, including the following: "Participating States will explore ways to work together to develop national capacities for nuclear forensics, such as the creation of national libraries and an international directory of points of contact, to facilitate and encourage cooperation between States in combating illicit nuclear trafficking."[49] The concept of national nuclear forensic libraries appears to gain acceptance and mechanisms have to be explored and implemented enabling queries and allowing information sharing.

Regional databases appear a viable compromise between national and international databases. For example, the database available at the Institute for Transuranium Elements of the European Commission covers data on (fresh) fuel for power reactors and includes information provided by some western European and Russian fuel manufacturers.[50] Data protection is ensured by strict confidentiality agreements and is supported by a complete physical isolation of the database from any network. Irrespective of whether nuclear forensic libraries are strictly national, regional, or international, their maintenance, and the continuous update and vetting of the data, are essential.

Many of these considerations refer to predetonation nuclear forensics. We have to recognize that nuclear weapon states have significant experience in postdetonation nuclear forensics. Nonweapon states and nonmilitary laboratories within weapon states have only very limited experience in this area, which builds on the analysis of the limited amounts of openly available material such as trinitite.[51] This is unlikely to change in the future.

A more general challenge for nuclear forensics is the sustainability of technical capabilities. The challenge is actually twofold. First of all, the global nuclear workforce is aging, and there is a significant risk that tacit knowledge is not transferred to the next generation of scientists. Secondly, nuclear forensic investigations occur at low frequency. For maintaining the skills, nuclear forensic capabilities should be established at laboratories, where the analysis of nuclear material is performed on a routine basis. Typically, this would be for other non-security purposes, such as environmental or quality control, and ensures the availability of appropriate infrastructure and measurement equipment, of validated analytical techniques, and of suitably qualified experts. However, there are also many new potential security-related applications on the horizon. Nuclear forensic approaches to support arms control verification appear particularly promising. For the verification of the NPT, nuclear safeguards methodologies are already being complemented with investigative techniques transferred from the nuclear forensics area. In addition to maintaining capabilities for the current missions of nuclear forensics, it is therefore critically important to further develop and demonstrate relevant nuclear forensic techniques now so that they will be available when new challenges and opportunities arise.

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